2. RANGE OPERATIONS, CONTROLS AND SAFETY

2.1 RANGE CHARACTERISTICS FOR SAFE OPERATION

2.1.1 US Government Launch Sites

The US Government has traditionally operated separate civilian and military space programs. NASA is the lead agency for civilian space activities, and assists as necessary, the Departments of Energy, Interior, Commerce, Transportation and Agriculture which also maintain space research and utilization programs.

The US Space Command (US SPACECOM) coordinates all military space activities, but the three services also have operational Space Commands. DOD recently established a Consolidated Space Test Center (CSTC) under the Space and Missile Test Organization (SAMTO). A very recent DOD regulation governing military Range activities designated the Air Force as the lead agency for the tri-service conceptual Space Test Range at Onizuka AFB, in California, with a special focus on safety issues.

The Eastern Test Range (ETR) is under the direction of the USAF Eastern Space and Missile Center (ESMC) at Patrick Air Force Base, Florida, and the Western Test Range (WTR) is under the direction of the USAF Western Space and Missile Center (WSMC) at Vandenberg Air Force Base, California. WTR launches are from Vandenberg Air Force Base; ETR launches are from the Cape Canaveral Air Force Station (CCAFS). NASA space missions are launched from the Florida Kennedy Space Center (KSC), also on Cape Canaveral and occasionally from WFF.

The United States has a major launch site in Florida at Cape Kennedy (NASA) and CCAFS (DOD) for manned, lunar and planetary launches, and for launching satellites to geostationary orbit (primarily for weather and communications). It has another major West Coast launch site at Vandenberg Air Force Base (VAFB), California, for satellites (including weather, Earth resources, navigation and reconnaissance) which must go into polar orbits. A smaller launch site for small space payloads and for sub-orbital research rockets is the NASA/Goddard Space Flight Center (GSFC) Wallops Flight Facility (WFF) site at Wallops Island, Virginia. Sub-orbital launches and short-range vertical testing are accomplished at White Sands, New Mexico, from the White Sands Missile Range (WSMR). In addition, the US Government has conducted launches from a number of other CONUS and off-shore sites.

Each of the National Ranges has unique capabilities related to its mission, siting and facilities, as well as specific requirements for the Range Users (see Vol. 3, Chs. 9, 10). The safety philosophy of ground and Range operations is generally that of dealing with controlled, managed and acceptable risks. Procedures have been established to handle and store all materials (propellants, etc.) which may be a hazard, control and monitor electromagnetic emissions and govern transportation of materials to and from the facility.[4] The storage of propellants and explosives used in Expendable Launch Vehicles (ELV's) is controlled by quantity-distance criteria, as specified.[3] Failure modes and effects analyses (FMEA) are prepared, when necessary, for all potentially hazardous activities and devices (see Ch. 8). Quantitative risk analysis has rarely been used to establish launch and space operational risk because of the conservative philosophy of vehicle design, ground and launch procedures and the difficulty in developing realistic estimates of hazardous event probabilities and accident scenarios (see discussion in Vol 3, Chs. 9 and 10).

Since there are currently no private commercial space launch range facilities in the US, we will describe the past and current practices at US Government Range facilities. It is assumed throughout this report that the level of operational safety at licensed commercial space facilities will be comparable or equivalent to the level of safety maintained at US Government Ranges.

2.1.2 Ground Operations and Safety

One of the principal responsibilities of the launch Range is to perform all of those tasks which eliminate, or at least acceptably minimize, the hazards from an expendable launch vehicle (ELV), both prior to and during the launch.[1-3] This is accomplished by establishing:

(1) requirements and procedures for storage and handling of propellants, explosives, radioactive materials and toxics;
(2) performance and reliability requirements for flight termination systems (FTS) on the vehicle;
(3) a real-time tracking and control system at the Range; and
(4) mission abort, vehicle destruct or flight termination criteria which are sufficient to provide the necessary protection to people both within (on- Range) and outside (down-Range) the boundaries of the launch facility.

At each Range there is a hierarchy of regulations and requirements for Ground and Launch safety implementation (see also Chs. 6, 7, Vol. 2). Generally, the National Ranges take responsibility for the vehicle handling and safe operation from receipt until the time of orbital insertion. Safety issues associated with on-orbit impacts and re-entry from orbit are not normally the responsibility of the Range (see Chs. 6, 7, Vol. 2).

Control of public risks from jettisoned stages and hardware prior to orbital insertion are a Range responsibility.

The following sections provide a general introduction to the various aspects of planning, ground operations and flight control, all with a specific emphasis on safety. Chapter 10 in Vol. 3 provides a more detailed discussion of launch hazards and their minimization by Range Safety controls.

2.1.3 Range Safety Control System

The NASA "Range Safety Handbook" states: "The flight safety goals are to contain the flight of all vehicles and preclude an impact which might endanger human life, cause damage to property or result in embarrassment to NASA or the US Government. Although the risk of such an impact can never be completely eliminated, the flight should be carefully planned to minimize the risks involved while enhancing the probability for attaining the mission objectives."(7)

The real-time Range Safety (or Flight) Control System must accurately and reliably perform the following functions:

(1) Continually monitor the launch vehicle performance and determine whether the vehicle is behaving normally or failing;

(2) Track the vehicle and predict (in real-time) where the vehicle or pieces of the vehicle will impact in case of failure and if flight termination action is taken;

(3) Determine if there is a need to delay or abort the launch or destruct the vehicle, based on a comparison of predetermined criteria with the current vehicle status; and

(4) If necessary to protect the public, send a command to abort the mission either by vehicle destruct or engine shutdown (thrust termination). Note that the term "destruct" is used generically in this report to denote flight termination actions for Range Safety purposes. In reality, thrust (and the flight) can be terminated on command for some ELV's without vehicle destruction.

Figure 2-1 describes pictorially the activities of the various elements of the Range Safety Control System.

Vehicle performance is determined at all Ranges by visual observation (early in flight) and by real-time telemetry measurements of vehicle status as a back-up to the computed (wind-corrected) behavior of the instantaneous impact point (IIP), discussed below in more detail. The actual location of the vehicle is less important than where the vehicle and its debris will land in case of both normal operation, accidental failure, abort or destruct. Therefore, in tracking a vehicle, velocity data must be obtained either directly or by differentiating successive measures of position. The most frequently used method of obtaining the velocity and position data has been the use of radar trackers, which measure the vehicle position in terms of azimuth, elevation and range relative to the tracker, expressed in a launch-pad centered reference coordinate system. Radars are also capable of

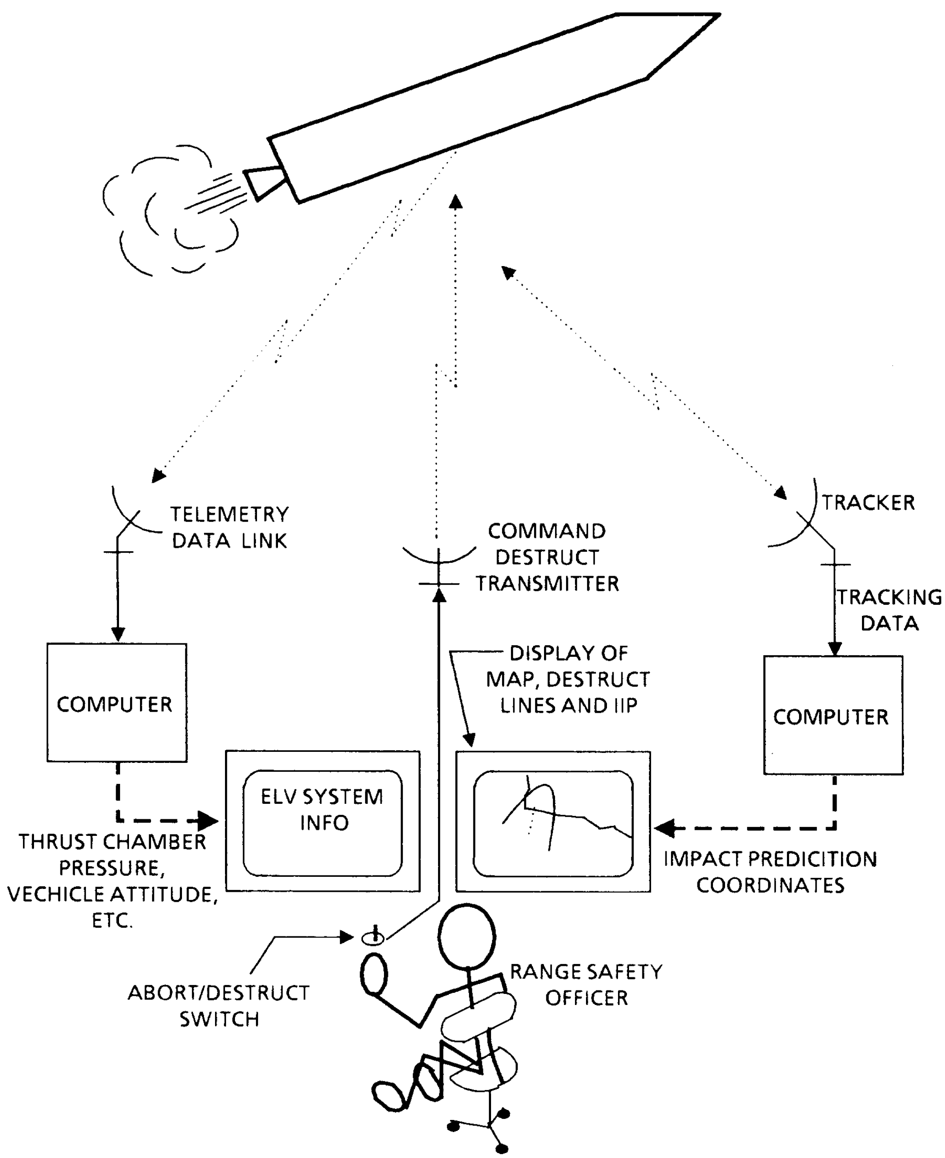

FIGURE 2-1. ELEMENTS OF THE FLIGHT CONTROL SYSTEM

determining range rate, i.e., the rate at which a vehicle is moving toward or away from the radar. A single tracker near the launch pad can provide satisfactory information for two or more minutes of flight depending on the rate at which the launch vehicle is traveling away from the tracker. The quality/accuracy of the tracking data is often affected by several factors, two of which are: (1) multi-path of returned signals which occurs at low antenna elevation angles; and (2) the plume signal attenuation due to high temperature ionization caused by the solid rocket motor exhaust. Multiple radar trackers are used to minimize these problems and to provide redundant measurements, so that failure of a single tracker will not jeopardize the mission. Early in flight, when the launch vehicle is still close to the ground, the radar may not be able to track the vehicle. In this case, visual observation and telemetry may be the only means of determining whether there is a malfunction and whether the vehicle maintains the correct attitude. Position and velocity data, along with the predicted instantaneous impact point (IIP) are typically displayed in real-time in the Launch Control Center (LCC).

Although not yet applied at the National Ranges, it is possible to use satellite information for determination of vehicle position and velocity. An electronics package on board the launch vehicle could collect information for calculating the range relative to several separately located navigation satellites and could be telemetered to a ground station, processed and converted into vehicle position and velocity. This will become practical when the Global Positioning System (GPS) satellites become operational. Some Ranges have used three or more geographically spaced telemetry antennas and associated computer equipment to infer the vehicle position and velocity from the Doppler phase shift of the received telemetry signals.

The launch vehicle velocity and position information are generally used to compute an instantaneous impact point (IIP). The IIP is displayed on a screen or chart indicating where the vehicle will impact on the surface if flight were to be aborted at that instant. This impact point is usually computed, assuming no atmosphere, as a vacuum IIP (VIIP) which allows simpler and more rapid trajectory computation. Inclusion of atmospheric drag is generally not necessary to satisfy the objectives of the real-time Range Safety. However, a drag and wind correction is applied in some cases.

Early in the flight the IIP advances slowly, but as the vehicle altitude, velocity and acceleration increase, the IIP change rate also increases. Very early in flight, the IIP change rate increases from zero to several miles per second. Later, it increases to tens of miles and then hundreds of miles per second. As the vehicle reaches orbital velocity, the IIP rate essentially goes to infinity because the vehicle will no longer come down.

The difference between the advance of the IIP and the present position (sub- vehicle point) (SVP) is illustrated in Figure 2-2. It is the advancing IIP that the Range Safety Officer (RSO) is usually observing during a launch. Prior to the launch, a map is prepared with lines drawn to represent the limits of excursion which, when exceeded, will dictate a command signal to terminate flight. A typical set of "destruct lines" is shown in Figure 2-3.

The destruct lines are deliberately offset from land or populated areas to accommodate: (1) vehicle performance characteristics and wind effects; (2) the correction for using a vacuum instead of a drag- corrected impact point; (3) the scatter of vehicle debris; (4) the inaccuracies and safety-related tolerances of the vehicle tracking and monitoring system; and (5) the time delays between IIP impingement on a destruct line and the time at which flight termination actually takes place (i.e., human decision time lag). By proper selection of the destruct lines, debris can be prevented from impacting on or near inhabited areas.The ability of the system to accurately predict the ELV impact point diminishes as the vehicle advances into the flight and the IIP is moving more rapidly along the ground track. Consequently, the difficulties in performing the Range Safety Control function increase with time, particularly if there are land masses or population centers that must be protected near the ground path of the launch trajectory. Regardless of the flight time, the Range Control problem is always more difficult if the flight plan is designed to move close to or over a populated area. If a flight plan requires violation of a prudently designed abort line, a risk analysis is performed to determine if the risk is acceptable. If the risk is small enough, the Range Commander may choose to permit a launch without an abort line for portions of the flight (for further discussion see Vol. 3, Ch. 10).

2.2 LAUNCH PLANNING

The principal mission of Range Safety personnel is the protection of life and property both off and on-site at the launch facility. In keeping with that objective, the Range must not be negligent, nor impose undue restrictions on launch conditions, that could result in a high probability of a good vehicle being destroyed. Minimization of the probability of terminating a "good" flight, and simultaneous minimization of the potential risk due to a malfunctioning ELV, is accomplished through careful mission planning, preparation and approval prior to the launch. The planning is in two parts: (1) mission definition such that land overflights or other risky aspects of the launch are avoided and/or minimized; and (2) development of data which support the real-time decision and implementation of active control and destruct activities. These two aspects are discussed in the following subsections.

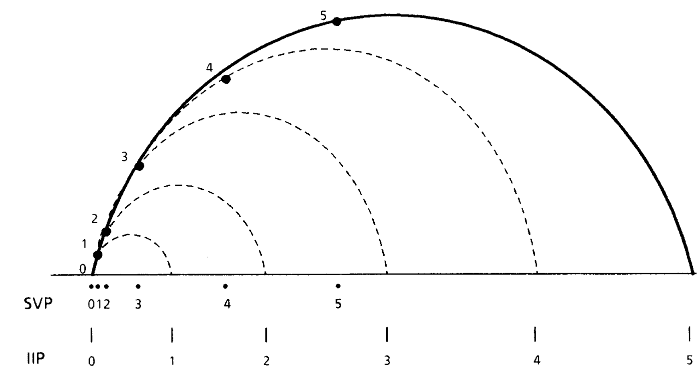

FIGURE 2-2. INSTANTANEOUS IMPACT (IIP) AND SUB-VEHICLE POINTS (SVP)

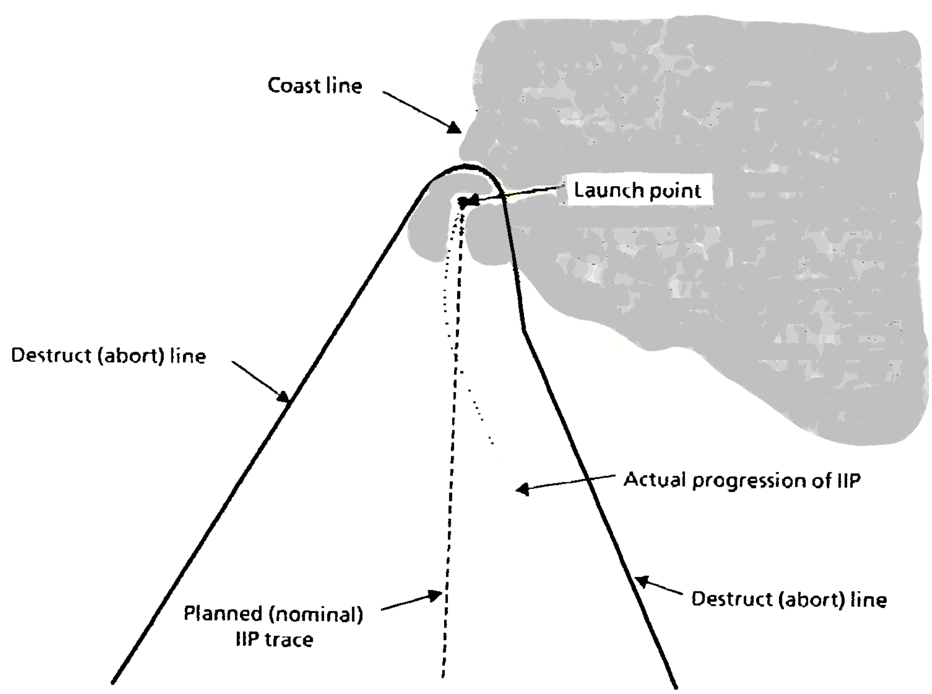

FIGURE 2-3. TYPICAL IIP AND DESTRUCT LINE DISPLAY

2.2.1 Mission Planning

Figure 2-4 contains a map showing the ground trace of a hypothetical launch from Vandenberg Air Force Base (VAFB) on an azimuth which causes overflight of islands south of the base, flight along the coast and overflight of a portion of Chile and Argentina (in fact, such azimuths are restricted, as discussed in Ch. 10). The greatest risk is in the immediate vicinity of the launch area and to any occupants of the nearby islands. Since the overflight of these islands is planned, abort lines cannot protect their inhabitants. Abort lines can protect the coast from vehicle overflight and debris impacts, in case of destruct. However, if the intended flight path is too close to the coast and the abort lines are too close to the planned flight path, there is the possibility that the IIP of a good, but slightly drifting, vehicle will cross the abort line and thus require a commanded destruct. The overflight of the tip of South America is not as serious a problem because the rate of advance of the IIP is so rapid and the vehicle altitude is so high at that point in flight that there is a much smaller possibility of any hazard to that region. A failure would have to occur within a specific time interval (a second or two of flight) in order for any resulting debris to impact the region (see Ch. 10 for a more in-depth discussion of such risks).

In addition to considering where the aborted or destroyed vehicle will land, one must also consider where the debris from normally jettisoned spent stages will impact. For example, the vehicle might fly safely over the islands, but drop an empty rocket casing on one of them. Mission planning must consider and avoid all of the hazards associated with normal launch operations, as well as other potential hazards associated with potential accidental failures for the particular launch plan.

A Range user may request a particular trajectory to satisfy desired mission requirements (i.e., orbital inclination) or payload constraints. For example, a trajectory having a more easterly azimuth will enable the vehicle to put a heavier payload into orbit. If the launch vehicle is limited in lift capacity, the Range user may try to get the most favorable launch azimuth (in this case, eastern) in order to increase the amount of payload the vehicle can place into orbit. The Range Safety function in the mission planning stage is to limit the range of allowed launch azimuths to those which keep the risk to people on the ground at acceptably low levels. Another mission planning responsibility is to evaluate all other aspects of the planned launch, e.g., impact points of jettisoned stages, to assure the acceptability of the overall risk of the mission.

There are situations where the conflict between safety requirements and mission objectives require special studies to determine risks and define tradeoffs. In these cases detailed

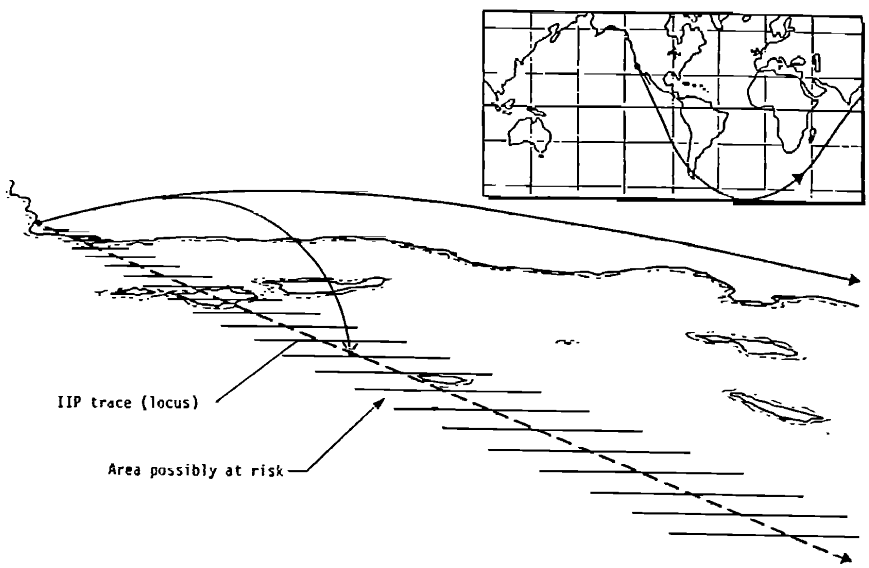

FIGURE 2-4. A HYPOTHETICAL AND RISKY TRAJECTORY PLAN

risk analyses are performed using models that consider the probability of the vehicle failing in a variety of modes and simulate the behavior of the missile during and after malfunction,including the effect of activating the flight termination system.

Such risk analyses usually compute the land impact probability and associated casualty expectation (the average number of casualties expected per launch). Typically, missions with casualty expectations of less than one in a million are considered reasonably safe. If the risks are higher, the mission ordinarily comes under more scrutiny (see Chs. 9, 10 for more detailed discussion).

One of the options for maintaining a low risk for a launch is to move the abort lines away from the populated areas and closer to the trace of the IIP for the nominal trajectory. While this decreases the overall launch risk, it increases the probability of aborting a good vehicle. Considering the very high value of many of the launch vehicles and their payloads, these tight abort lines put additional pressure on the Range Safety Officer (RSO) who must decide on an active destruct command.

Another option to minimize the risk of a normal, or failed, launch to the population surrounding the Range is to place much tighter constraints on the tolerable wind and other meteorological conditions at the time of the launch.

2.2.2 Standard Procedures to Prepare for a Launch

The National Ranges have provided standards and requirements for organizations desiring to launch vehicles from their facilities. For example, the United States Air Force has specific safety requirements issued for each of the Ranges under USAF control. These documents describe the safety policy and procedures and also define the data submittal and launch preparation requirements for the Range user.(1,2) The categories covered by these requirements include ground safety (handling of propellants, ordnance, noise, hazardous operations, toxics, etc.), flight analysis (vehicle trajectory, mission, etc.), flight termination systems (FTS), ground operations and flight operations. Included in the flight analysis portion are requirements for trajectory modeling and descriptions along with the dynamic characteristics of the vehicle during a malfunction turn.This information is used by Range personnel to construct the abort lines. Ref. 5 is an example of the equipment requirements to support typical missions from a National Range.

REFERENCES TO CHAPTER 2

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4. Hazards of Chemical Rockets and Propellants Handbook: Vol. I, General Safety Engineering Design Criteria; Vol. II, Solid Rocket Propellant Processing, Handling, Storage, and Transportation; Vol. III, Liquid Propellant Handling, Storage, and Transportation. CPIA 394, Vol. I, II, and III. Chemical Propulsion Information Agency, 8621 Georgia Ave, Silver Spring MD 20910, September, 1984.

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7. "Range Safety Handbook", NASA GHB 1771.1, Sept. 1984.